Design of Kalman Filter to Estimate Heart Rate Variability from PPG Signal for Mobile Healthcare

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***Abstract*— In the mobile healthcare system, a very important vital sign in analyzing the status of user health is the HRV (heart rate variability). The used signals for measuring the HRV are electrocardiograph and PPG (photoplethysmograph). In extracting the HRV from the PPG signal, an important issue is that extract the exactly HRV from PPG signal distorted from the user's movements. This study suggested a design method of the Kalman filter to solve the problem, and evaluated the performances of a proposed method by PPG signals containing motion artifacts. In the results of experiments that compared with a variable step size adaptive filter proposed in recently, the proposed method showed better performance than an adaptive filter.**

***Index Terms*— PPG(photoplethysmograph), HRV(heart rate variability), Kalman filter, Motion artifacts**

I. INTRODUCTION

IN the mobile healthcare system, the most popular kinds of vital signs for monitoring are heart rate, heart rate variability, oxygen saturation, skin temperature, blood pressure, respiration rate, etc [1]~[5]. Specially, the heart rate variability (HRV) of these vital signs is a very important factor in analyzing the status of user health. The HRV is used to diagnose heart disease, emotion, stress index, and the autonomic nervous system [4][5]. The typical signals to measure the HRV are electrocardiograph and photoplethysmograph. In the signals, the PPG signal is changes of blood volume and perfusion in skin and is acquired by a non-invasive optical technique [6][7]. Also, the PPG signal contains components that are synchronous with cardiac rhythms. The signal in the mobile healthcare system is widely used to extract the HRV, degree of arterial stiffness, and oxygen saturation. In developing the mobile healthcare device using the PPG signal, the most important issue is to minimize the distortion of PPG signal from the user's movements. We called a motion artifact that is the noise signal generated from the movements. Namely, the motion artifacts are the noise generated from hand swing, finger banding, and wrist moving. It is difficult to remove the motion artifact because the frequency spectrum bands of these motion artifacts are overlapped with frequency band of PPG signal [8]~[10]. In the last few years, many researchers to improve the problem developed several signal processing algorithms [8]~[15]. The suggested methods in their articles are to remove the noise through an adaptive filter and accelerometer. These methods are shown good performance but this method involves additional cost or ECG signal. Therefore, we need the novel signal processing method for the mobile healthcare device which can process the heart beat detection without the additional sensor or signal. This study suggested the design method of a Kalman filter [16] to extract the HRV from PPG signal, and evaluated its performances from PPG signals containing motion artifacts.

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II. RELATIONSHIP BETWEEN PPG SIGNAL AND MOTION ARTIFACTS

The PPG signal is a non-invasive optical technique that measures changes in skin blood volume and perfusion [6]~[11]. The PPG signal contains components that are synchronous with respiratory and cardiac rhythms. The PPG signal is acquired by illuminating skin with light $P_{LED}(k)$ generated from an infrared or red light emitting diode (LED) and then measuring the amount of light either transmitted or reflected in a photo-diode :

$$S(k) = P_{LED}(k)e^{-\Delta d} \tag{1}$$

In Eq. (1), S(k) is PPG signal generated from variation Δd of distance due to pulsation Δd of artery. The variation Δd is affected from respiration and user's movements [6]~[9]. The frequency band of PPG signal is overlapped with frequencies of respiration signal and motion artifacts as shown in Figure 1. It is difficult to extract the PPG signal by linear filters. So, we need a novel algorithm for extracting the HRV from PPG signal containing motion artifacts.

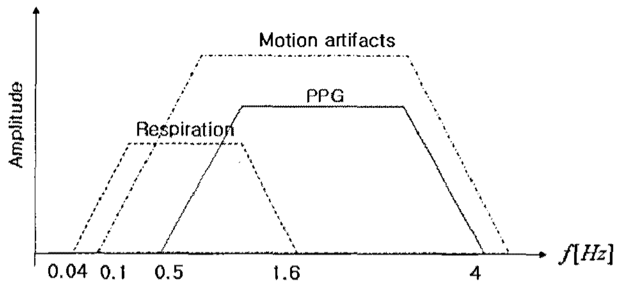

Fig. 1. Frequency bands of respiration, PPG signal, and motion artifacts.

III. DESIGN OF KALMAN FILTER

The study proposes a design method of the Kalman filter to extract HRV from the measured PPG signal containing the motion artifact. The proposed method is based on the harmonic characteristics [17] of PPG signal and motion artifacts. The most energy of PPG signal in the frequency spectrum is in ranges of 0.8~2.0 [Hz]. The bands except the frequency band can be considered as the noise. The mixed noises of the measured PPG signal can reduce it by using the covariance of signal values in noise bands.

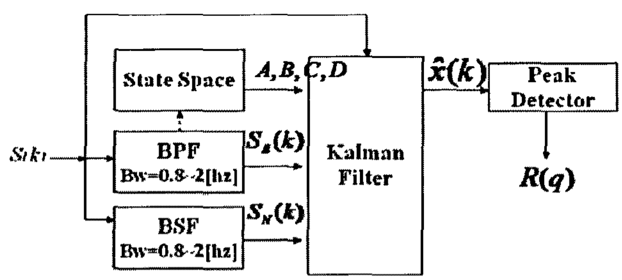

Fig. 2. Proposed method to extract HRV from PPG signal.

In other words, if the noise signal $s_N(k)$ at k time is the sum of the respiration signal $resp(k)$ and motion artifact $motion(k)$, the measured PPG signal $s(k)$ defined as follows:

$$\begin{aligned} s(k) &= ppg(k) + \{resp(k) + motion(k)\} \\ &\approx s_B(k) + s_N(k), \end{aligned} \tag{2}$$

The PPG signal $s(k)$ of Eq. (2) can divide between the two signals $\{s_B(k)=ppg(k),\ s_N(k)=resp(k)+motion(k)\}$ by BPF (band pass filter) and BSF (band stop filter), and Eq. (2) can represent a difference equation as follows:

$$s(k) = \frac{1}{a_0}[\sum_{i=0}^{P} b_i s(k-i) - \sum_{j=1}^{Q} a_j s_B(k-j)] + s_N(k) \tag{3}$$

where, $a(q)$ and $b(q)$ are coefficients of BPF with the general causal IIR filter, and P and Q are the feedforward filter order and feedback filter order. The transfer function of the BPF for $s_B(k)$ is as follows:

$$\begin{aligned} H(z) &= \frac{S_B(z)}{S(z)} = \frac{b_0 + b_1 z^{-1} + \dots + b_P z^{-P}}{1 + a_1 z^{-1} + \dots + a_Q z^{-Q}} \\ &= b_0 + \frac{(b_1 - b_0 a_1) z^{-1} + \dots + (b_N - b_0 a_N) z^{-N}}{1 + a_1 z^{-1} + \dots + a_N z^{-N}} \end{aligned} \tag{4}$$

where, $N=max(Q,P)$, with $a_i=0$ for $i>Q$, and $b_i=0$ for $i>P$. In Eq. (3), we can assume the signal $s_N(k)$ to the process noise $n_P(k)$, and process noise $n_P(k)$ is obtained by BSF. The process noise covariance $\mathbf{N}_P(k)$ is

$$\mathbf{N}_P(k) = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{cov}(s_N(k), s_N(k-1), \dots, s_N(k-W-1)) \tag{5}$$

where, W is a number of previous values obtained by the BSF. To reduce the motion artifacts within PPG signal by using the process noise, this study used Kalman filter, which is shown good performance in estimating the states of the system. The Kalman filter to estimate the states from the measured signal consists of three equations [16].

$$\mathbf{K}(k) = \mathbf{AP}(k)\mathbf{C}^T(\mathbf{CP}(k)\mathbf{C}^T + \mathbf{N}_P)^{-1} \tag{6}$$

$$\hat{\mathbf{x}}(k+1) = [\mathbf{A}\hat{\mathbf{x}}(k) + \mathbf{B}s(k)] + \mathbf{K}(k)[y(k+1) - \mathbf{C}\hat{\mathbf{x}}(k)] \tag{7}$$

$$\mathbf{P}(k+1) = \mathbf{AP}(k+1)\mathbf{A}^T + \mathbf{N}_M - \mathbf{AP}(k)\mathbf{C}^T\mathbf{N}_P^{-1}\mathbf{CP}(k)\mathbf{A}^T \tag{8}$$

where, $\mathbf{K}(k)$ is Kalman gain; $\mathbf{A}$ is the $N \times N$ state transition matrix; superscript -1 is matrix inversion; superscript T is matrix transposition; $\mathbf{C}$ is an output matrix, $\mathbf{B}$ is a control matrix, $\mathbf{P}(k)$ is an estimation error covariance, and $\mathbf{N}_M$ is a measurement noise covariance. In applying the proposed method to the Kalman filter, we have to convert the BPF transfer function (Eq. (4)) into the linear state space equation as follows:

$$\mathbf{x}(k+1) = \mathbf{Ax}(k) + \mathbf{B}s(k) \tag{9}$$

$$y(k) = \mathbf{Cx}(k) + \mathbf{D}s(k) \tag{10}$$

where, $y(k)$ is the measured PPG signal, and matrix $\mathbf{A}$, $\mathbf{B}$, output vector $\mathbf{C}$, and $\mathbf{D}$ are defined as:

$$\mathbf{A} = \begin{bmatrix} -a_0 & -a_1 & \dots & -a_N \\ 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \tag{11}$$

$$\mathbf{C}=\begin{bmatrix}(b_1-b_0a_1)\\(b_2-b_0a_2)\\\vdots\\(b_N-b_0a_N)\end{bmatrix}^T,\quad \mathbf{D}=b_0 \tag{12}$$

From the above equations, we can extract PPG signal $\hat{y}(k)$ from the estimated state vector $\hat{\mathbf{x}}(k)$. The peak detector to extract intervals of the heartbeats from PPG signal is consisted as follows:

$$r(p)=\begin{cases} y_{\max}=0, & \textit{initialize}\\ k, y_{\max}=\hat{y}(k), & \hat{y}(k)\geq 0 \textit{ and } \hat{y}(k)\geq \hat{y}_{\max}\\ p=p+1, & \textit{otherwise}\end{cases} \tag{13}$$

$$R(q)=\frac{1}{I}\sum_{i=0}^{I-1}|r(p-i)-r(p-i-1)|T_s \tag{14}$$

where, $y_{\max}$ is the present maximum value, and Ts is a sampling time. Eq. (13) and (14) are used to find the index k of the maximum value in the area ($\hat{y}$>0) from the estimated PPG signal and I is an order of a moving average filter to extract the smooth rhythm from intervals of peaks.

IV. EXPERIMENTS AND RESULTS

In the study, the proposed algorithm was implemented based on MATLAB language. The experiments were performed for 60s to acquire PPG signals containing motion artifacts from the finger of the right hand and a reference PPG signal from the finger of the left hand by the PPG amplifier system (PPG-Kit, Physiolab Co.). In order to experiment, the set parameters of each filter are showed in Table I.

TABLE I
PARAMETERS OF FILTERS FOR EXPERIMENTS

Filters	Type	Orders
BPF, BSF	Butterworth, IIR filter	Feedforward filter order P=2, Feedback filter order Q=2
Kalman	Measurement noise	Random signal Variance =0.8
	Initial estimation error covariance,	Identity matrix
Sampling Frequency		100[Hz]

The state transition matrix, control matrix and output vector of the used BPF in the experiment are computed as follows:

$$\mathbf{A}=\begin{bmatrix}3.896 & -5.707 & 3.726 & -0.915\\ 1 & 0 & \dots & 0\\ 0 & 1 & \dots & 0\\ 0 & 0 & 1 & 0\end{bmatrix},$$

$$\mathbf{C}=\begin{bmatrix}0.0037 & -0.0073 & 0.0035 & 0.0001\end{bmatrix},$$

$$\mathbf{D}=9.45\times10^{-4}\approx 0$$

In the study compared the performance of the proposed method and a variable step size adaptive filter method. The evaluation items are a degree of waveform distortion, peak detection error, and PPI error. The results showed in Figure 3 and Table II. In an analysis for signal distortion

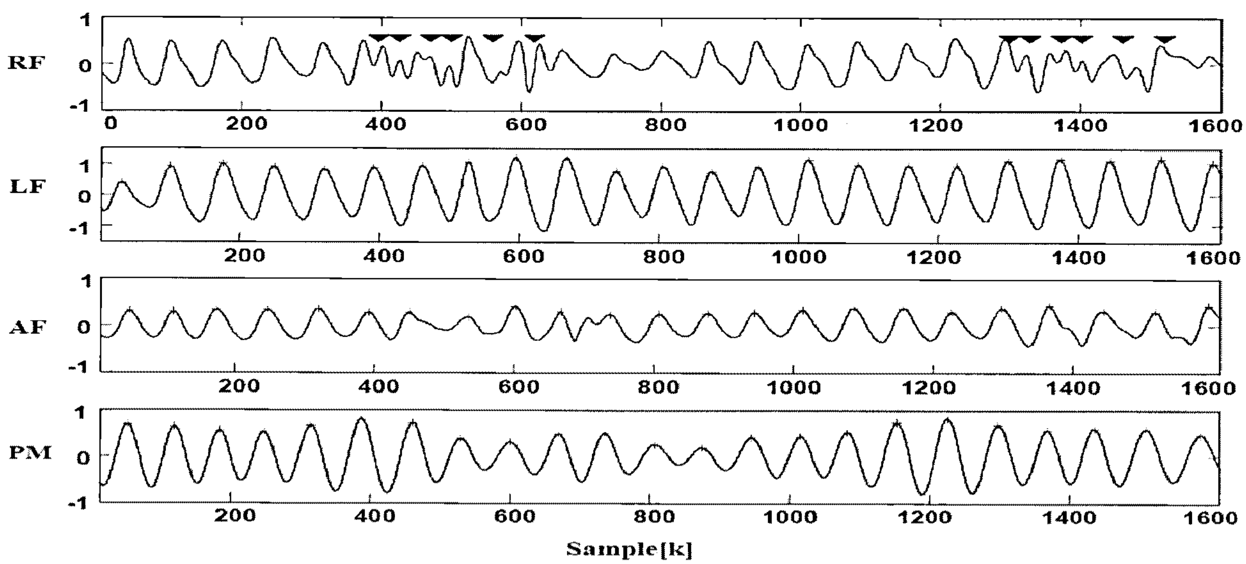

Fig. 3. Results for peak detection and signal distortion. (RF : PPG signal acquired at the finger of the right hand, LF : a reference PPG signal acquired at the finger of the left hand, mark(▼) : points of the generated motion artifact, mark(+) : peak point of heart beat, AF : a variable step size adaptive filter method, PM : proposed method).

from motion interference, the results (Fig. 3) of proposed method and AF method showed good results in case that user is in the rest state. Also, in case that user is in movement state, the proposed method showed good results than AF method. In an analysis (Table II) for peak detection, it showed the minimized PPI error and heart rate error than AF method.

TABLE II
ERRORS OF PPI AND HEART RATE

Items	PPI[sec]		HR[bpm]	
	AF	PM	AF	PM
Min	0.000	0.000	0.000	0.049
Max	0.137	0.030	15.440	3.842
Variance width	0.137	0.030	15.440	3.793

V. CONCLUSIONS

The HRV is a very important vital sign in diagnosing heart status, stress, etc. A simple method to measure the HRV in the mobile healthcare environment is to use the PPG signal. However, it is difficult to obtain precise heart rate and HRV from PPG signal containing motion artifacts. Therefore, to improve the problem, the study proposed a design method of the Kalman filter to filter motion artifacts. In the results of experiments which compared the performance of the proposed method and an adaptive filter, the performance of the proposed method showed the improved performance than AF method. Therefore, if the proposed method applies to the mobile healthcare device, we will be able to obtain the HRV of high quality.

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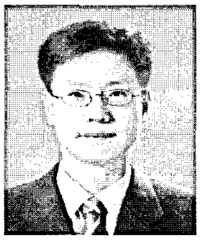

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